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The research of the lift, drag and pitching moment of a transport aircraft with slipstream effect of four turbo-propeller engines

Abstract

The slipstream effect of a transport aircraft with four turbo-propeller engines is studied by wind tunnel force test and seven-hole probe technique. The lift curve slope with slipstream increases by about 7% at typical climb condition. The zero lift drag coefficient increases by 19 and 76 drag counts at typical cruise and climb conditions respectively compared with non-slipstream condition, while the induced drag factor has a slightly decreasing trend. With slipstream effect, the pitching moment curve shows a sinusoidal type shape at different angle of attack (AOA), and the elevator efficiency is enhanced and reaches the peak between 10 to 12 degrees of AOA. The non-linear longitudinal stability and elevator efficiency is caused by the phenomenon that the wake of the slipstream sweeps from beneath the horizontal tail to above it with increasing AOA, which is proved by the wake flow field measured with seven-hole probe rake.

Keywords: slipstream, transport aircraft, turbo-propeller engine, flow field, seven-hole probe.

Introduction

Propeller engines are widely adopted by subsonic general aviation, military and civil transport due to its higher fuel efficiency at relatively lower speeds. Bronswijk[1] reviewed the history of the research of propeller power effect, and divided it to three stages: in the first period between 1920 and 1955, the major research works were done, such as the establishment of the blade element momentum theory, the theory and test study on single propeller, the interference between propeller and airframe, the effect of slipstream on aircraft stability and control, et al. In the period between 1955 and 1980, the interest on the application and research of propeller engines decreased rapidly due to the progress of turbojet and turbofan engines. NASA conducted full scale wind tunnel tests of serial general aviation aircrafts to improve the flight safety. After 1980 the higher fuel efficiency and thrust to weight ratio of turbo-propeller engines compared with the piston engine attracted the attention of the industry again. At the mean time the development of CFD made the modelling of the complex flow phenomenon of the slipstream effect possible with acceptable accuracy. Li [2] reviewed the research progress in slipstream effect and concluded that the researches mostly focused on lift, drag and pitching moment, while the study on roll moment, yaw moment and afterbody drag was not sufficient. The overall effects on aerodynamic force were studied in various tests but the research on the mechanism of slipstream-aircraft interference was not complete. Veldhuis[3] reviewed the calculations and tests about the propeller-wing interaction.

The interference between propeller slipstream and aircraft airframe is dependent on the specific configuration and is difficult to obtain the accurate data by analytical method. Numerical algorithms such as vortex lattice method with semi-empirical blade element model, and Euler/NS method incorporating equivalent plate model or sliding mesh technique can model the slipstream effect with reasonable accuracy. Rae suggested that propeller power effect consisted of direct force and slipstream. The slipstream has significant influence on lift, and affects the pitching moment by changing the downwash and blowing on the horizontal tail [4]. Petrov, Catalano, and Gentry studied the slipstream effect by wind tunnel tests and concluded that the propeller power effect increases the lift and decreases the longitudinal stability [5-7]. Hoerner concluded that the slipstream induced lift increment is proportional to thrust coefficient, but the ratio varies with different configurations. The zero lift drag of the component immersed in slipstream is proportional to the local dynamic, and the induced drag decreases [8-9].

The above mentioned researches usually do not separate the contribution of the direct force and slipstream, and the data of drag due to slipstream are lacking. The nonlinear pitching moment and elevator efficiency induced by slipstream are usually ignored. This research obtains the aerodynamic force increment induced by the pure slipstream by eliminating the contribution of the direct force realized by optimized test method, and adopts seven-hole probe technique to study the flowfield characteristics around the horizontal tail, revealing the mechanism of the slipstream-horizontal tail interaction.

Overview of the research

The scaled models of the transport aircraft with simulated propeller slipstream have been tested in three wind tunnels, including the AT-1 tunnel in Ukraine, the FL-12 and FL-13 tunnels in China Aerodynamics Research and Development Centre (CARDC). The test models are shown in figure 1, and wind tunnel and test parameters are shown in table 1. The test results in three tunnels are summarized to obtain the quantitative data of slipstream induced lift, drag and pitching moment, and the mechanism of the slipstream effect on the horizontal tail is revealed by flowfield measurement.

The slipstream effect is simulated by electric-powered model propellers with the thrust coefficient and advance ratio equal to real aircraft, thus the axial and rotational effect of the propeller slipstream are equivalent to the complete aircraft. Several typical thrust coefficients are selected to conduct the powered test, and the condition of the propeller is held constant during each test run. The direct force of the propeller is separated from the slipstream in all three tests. In AT-1 tunnel the propellers are driven by front-installed pneumatic rotors, which are detached from the aircraft model. In FL-12 and FL-13 tunnel, the propellers are powered by electric engines buried in the nacelle, and the forces of the propellers are measured by separate small balances and subtracted from the total force of the aircraft.

The thrust coefficient Ct indicates the intensity of the slipstream, and is defined based on the dynamic pressure q and wing area S of the aircraft, i.e.:

$$Ct=T/(qS) \tag{1}$$

In which T is the thrust of propeller engine. By adopting the definition the Ct is comparable with the drag coefficient of the aircraft.

The wake flowfield is measured by a seven-hole probe rake arranged as a rectangular matrix. The matrix has 4 rows and 7 columns, with 0.14m distance between neighboring rows and columns. The second row from the top is at the position of the MAC of horizontal tail, as shown in figure 2. The three vectors of velocity and the pressure are measured by the seven-hole probe. When analyzing the typical local velocity of different heights, the velocities of 7 points of each row are averaged.

Table 1 Parameters of wind tunnels and tests

	AT-1	FL-13	FL-12
Cross section size	4m*2.33m	8m*6m	4m*3m
Powered test speed	50m/s	55m/s	40m/s
Reynolds number (in millions)	0.8	1.7	0.6

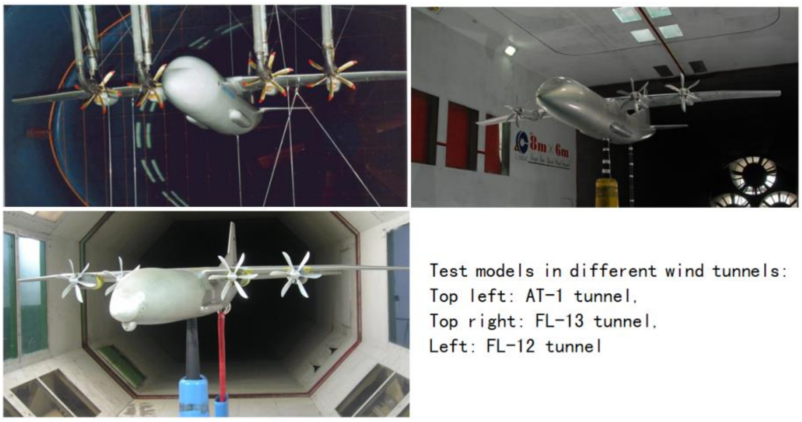

Figure.1 Wind tunnel test with simulated slipstream in different wind tunnels

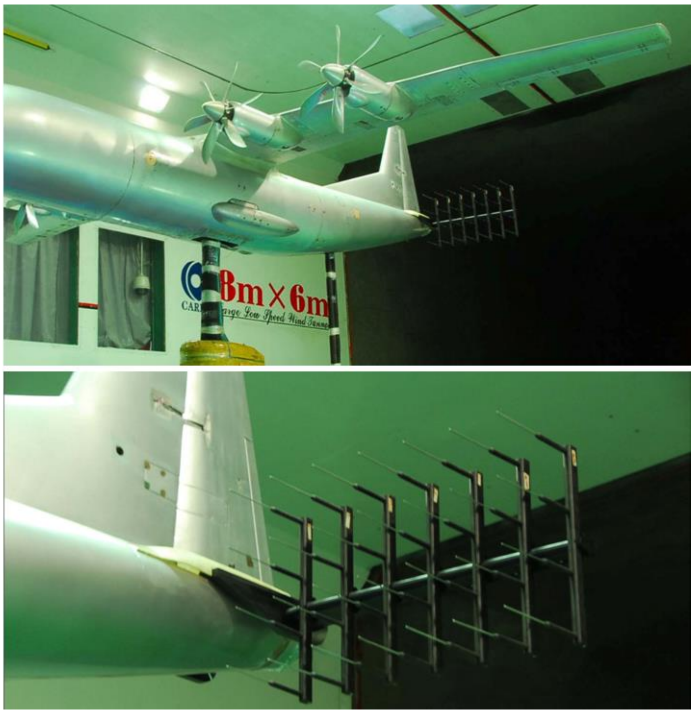

Figure.2 Flow field test with seven-hole probe rake

Test results and analysis

A. Lift and drag characteristics

The lift curves and lift curve slope of the aircraft in cruise configuration is shown in figure 3. It can be seen that the lift curve slope increases proportionally with Ct, and the lift curves of different Ct intersect at around 4 degrees of AOA. Eventually the lift coefficient has not significant change within normal flight range of AOA, which is attributable to the -4 degrees incident angle of the engine axis relative to the wing. The Ct at typical cruise and climb condition is 0.0114 and 0.0397 respectively, and the lift curve slopes are increased by 1% and 7% by slipstream respectively, which induce larger downwash effect at the horizontal tail. The influence of slipstream on the stall AOA of aircraft is small, but the maximum lift coefficient increases with higher Ct. However the complex nature of the stall and the interference between the wing and slipstream make the quantitative vale of C_{Lmax} with slipstream less accurate, and the possible factors are: the Reynolds number effect associated with the increased velocity in slipstream, the difference of the transition of the boundary layer, and the stall induced by the rotational flow of the slipstream, et al. Therefore, the accurate value of C_{Lmax} of propeller powered aircraft should be determined by flight test, but the slipstream does increase the C_{Lmax} by some extent as proved by the flight test of the aircraft.

The test results of drag characteristics of the aircraft with slipstream effect are shown in figure 4 to 7. The drag coefficient of the aircraft with slipstream is proportional to the square of the lift coefficient, similar to the non-slipstream condition. The zero lift drag coefficient C_{D0} increases in linear relationship with Ct, and the results from different tunnels show consistent trend. The C_{D0} increment at typical cruise and climb Ct is 0.0019 and 0.0076 compared with non-slipstream condition. This is caused by the higher dynamic pressure encountered by the aircraft components affected by the slipstream. For the aircraft the wing wetted area affected by the slipstream is 90% of the reference wing area. The induced drag parameter A_i drops slowly when Ct increases. The possible reason is that the increased lift curve slope due to slipstream flattened the drag curve of the components which are almost unaffected by slipstream such as fuselage and vertical tail. The variation of the lift distribution along the span and the change of downwash induced by slipstream are also the affecting factors and are difficult to be measured accurately. The overall effect of slipstream on lift-to-drag-ratio is negative, which drops by 6% and 20% respectively for typical cruise and climb condition compared with non-slipstream condition.

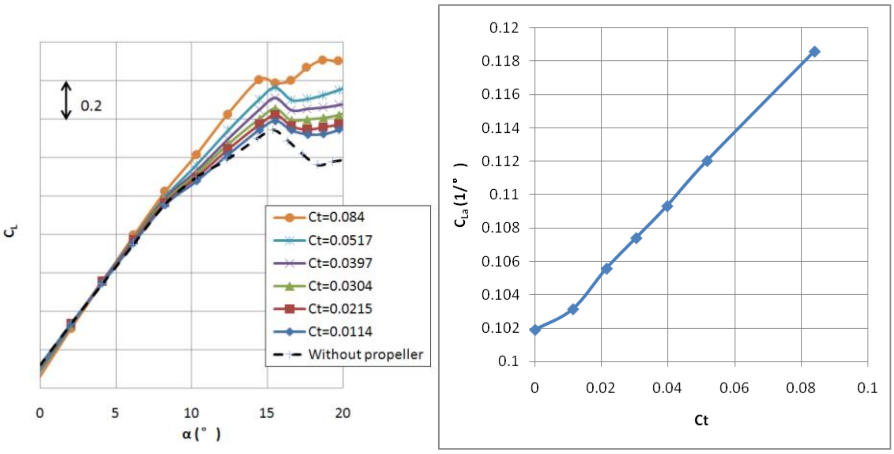

Figure.3 Lift curve with slipstream effect at cruise configuration

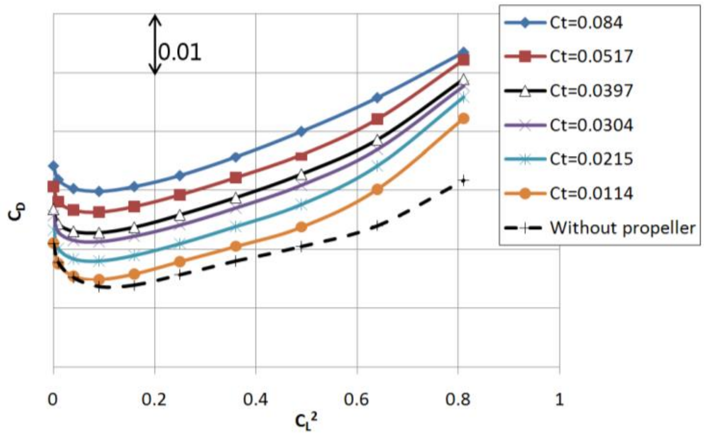

Figure.4 Drag characteristics with slipstream effect

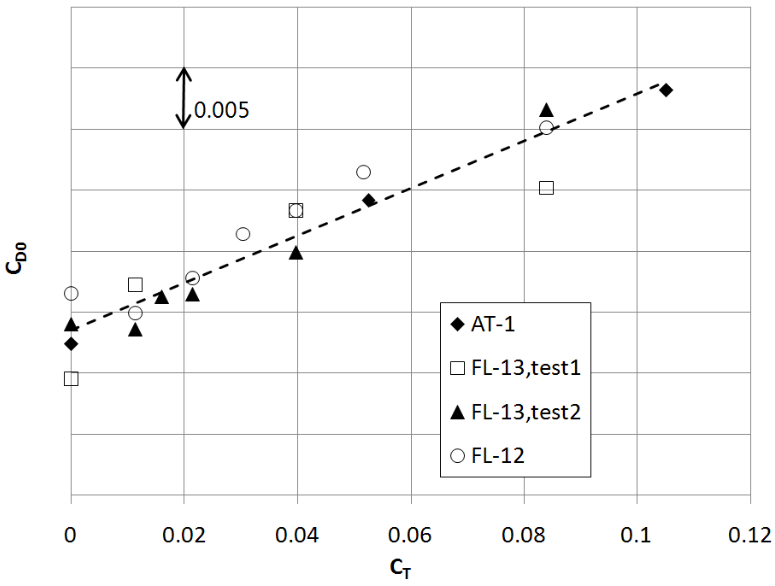

Figure.5 Zero lift drag coefficient at different thrust coefficient

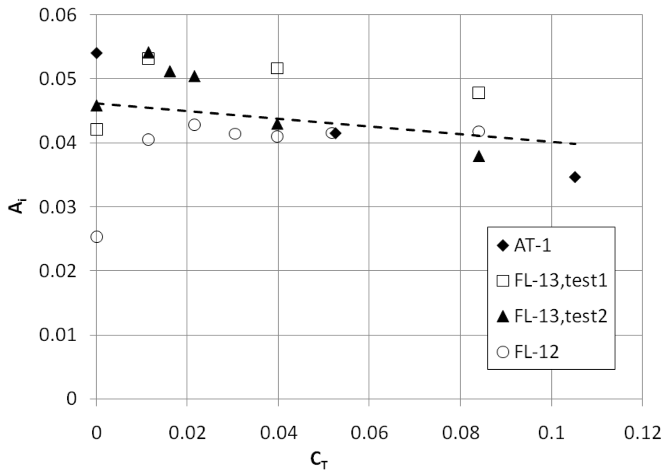

Figure.6 Induced drag factor at different thrust coefficient

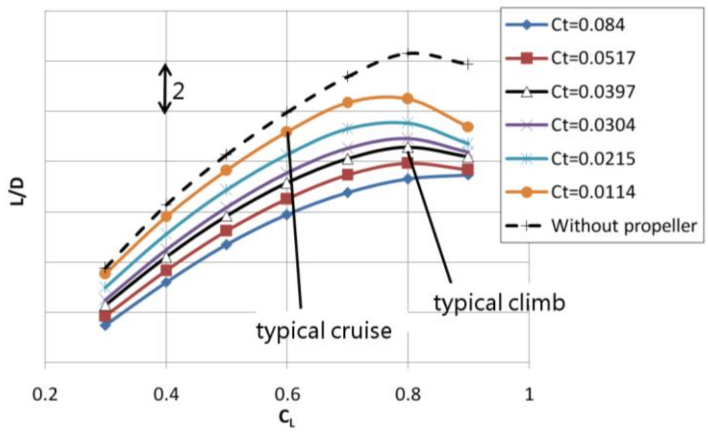

Figure.7 Lift to drag ratio at different thrust coefficient

B. Pitching moment and elevator efficiency

The pitching moment and elevator efficiency of the aircraft at cruise configuration are shown in figure 8 and 9. The pitching moment curves show strong nonlinear characteristics with slipstream effect. When the AOA is less than 10 degrees the slipstream induces nose-up moment and the peak appears at around 6 degrees. While the

AOA is larger than 10 degrees nose-down moment is induced by the slipstream, with the peak at 14 degrees. The pitching moment to AOA curves are similar to sinusoidal curves and are more obvious at higher Ct. The longitudinal stability increases when the AOA is between 6 and 14 degrees, but decreases at other AOAs.

The elevator efficiency increases by different magnitudes when the AOA is larger than 4 degrees and reaches the peak between 10 to 12 degrees. The increase of the elevator efficiency is caused by the larger dynamic pressure within the slipstream. Its variation proves that the relative position between the slipstream and the horizontal tail changes.

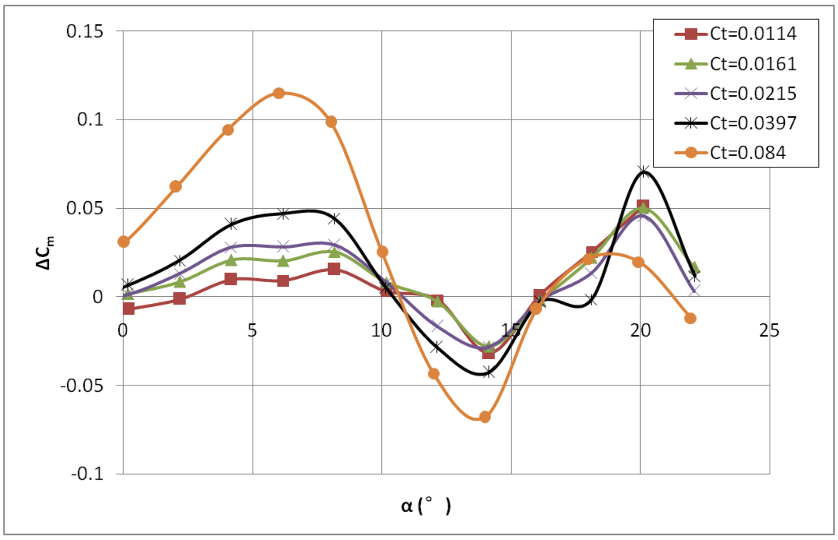

Figure.8 Pitching moment curve with slipstream effect

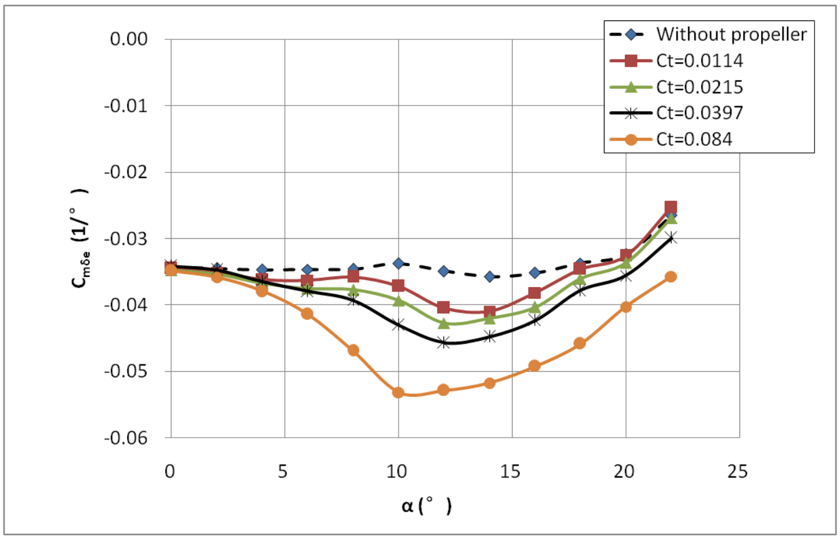

Figure.9 Elevator efficiency with slipstream effect

C. The flowfield near the horizontal tail

The flowfield characteristics around horizontal tail at different AOAs with slipstream are studied by tests, and the change of local speed due to slipstream is focused. The speeds tested by the 7 probes in each row are averaged to simplify the analysis, as shown in figure 10. It shows that the local speed of horizontal tail is increased when the AOA is higher than 4 degrees and reaches maximum at 14 degrees, which is slightly higher than the AOA where the elevator efficiency reaches maximum. The discrepancy can be explained by the lack of horizontal tail, which alters the local flowfield. The local speeds of different heights show that for the lower positions the increase of speed happens at smaller AOAs, vice versa. It can be derived that the space area affected by slipstream moves upwards when the AOA increases. The local speed is 1.3 times higher at maximum than the undisturbed speed when Ct=0.084.

The mechanism of the slipstream-horizontal tail interaction is proposed as shown in figure 11. Based on the force test and flowfield test, when the AOA is less than 10 degrees, the core of the slipstream is below the horizontal tail, and downward suction force is induced on the tail and the local speed increases for some extent. The core of the slipstream cross the horizontal tail at around the AOA of 10 degrees, and local speed reaches maximum without obvious direction of suction force. When the AOA is larger than10 degrees the slipstream core is above the tail which generates upward suction with increased local speed.

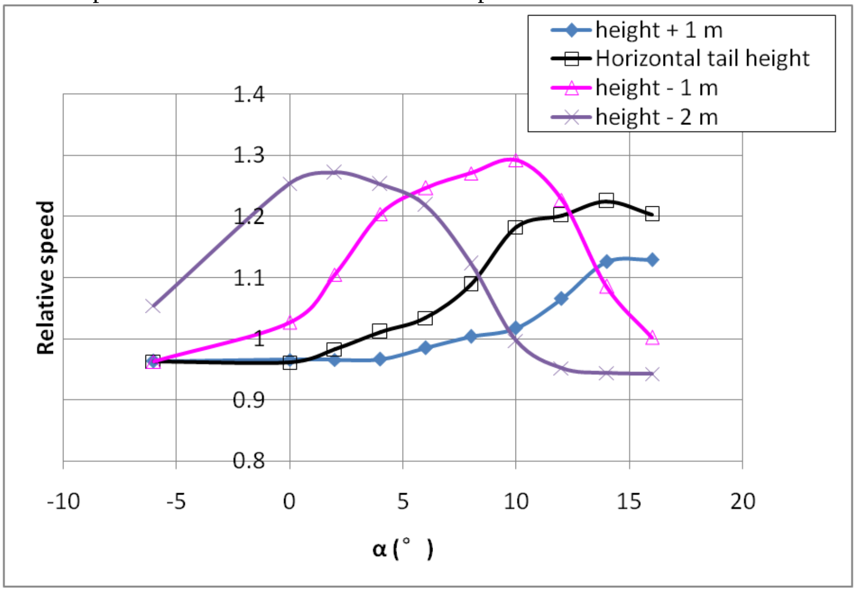

Figure.10 Slipstream wake flow test result（Ct=0.084）

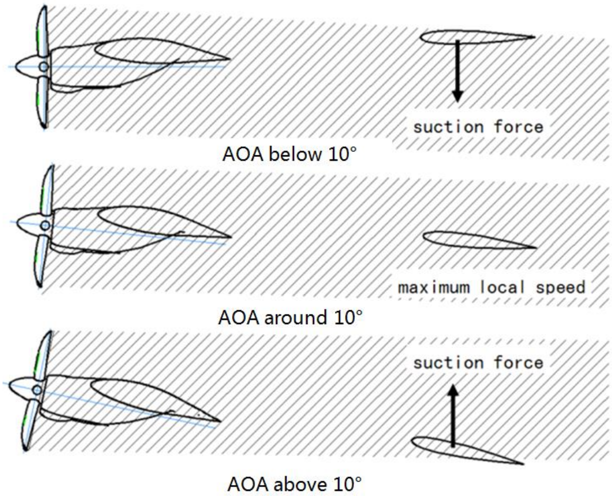

Figure.11 Draft of the slipstream sweeping across horizontal tail at different AOAs

Conclusion

The lift, drag and pitching moment increment due to slipstream at different AOAs are obtained by the test technique in which the propeller direct force is subtracted. The mechanism of nonlinear pitching moment and elevator efficiency is studied by the flowfield test around horizontal tail, and the slipstream sweeping across the horizontal tail when AOA increases is the major causal factor.

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